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ROBUST PRESSURE-ACTUATED LIQUID METAL DEVICES SHOWING RECONFIGURABLE ELECTROMAGNETIC EFFECTS AT GHZ FREQUENCIES (POSTPRINT)

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14. ABSTRACT
Pressure-actuated liquid metal devices are demonstrated for reconfigurable electromagnetic fundamentals at GHz frequencies, including tunable dipole antennas, switchable shielding with 35 dB attenuation, ~30 dB polarizer attenuation, and ~40 degree diffraction from a linear grating. In addition to a wide variety of electromagnetic effects, these devices are further advanced by: being highly physically flexible; in use of non-toxic GaInSn (68.5% Ga, 21.5% In, and 10.0% Sn) alloy as enabled by a sealed closed system with an acidic vapor background; and non-alloying/corrosion-resistant carbon inks for electrical connection. Collectively, this work addresses a wide variety of electromagnetic fundamentals, and the device construction advances required for real-world applications.

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Robust Pressure-Actuated Liquid Metal Devices Showing Reconfigurable Electromagnetic Effects at GHz Frequencies

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***Abstract*—Pressure-actuated liquid metal devices are demonstrated for reconfigurable electromagnetic fundamentals at GHz frequencies, including tunable dipole antennas, switchable shielding with 35 dB attenuation, ~30 dB polarizer attenuation, and ~40 degree diffraction from a linear grating. In addition to a wide variety of electromagnetic effects, these devices are further advanced by: being highly physically flexible; in use of non-toxic GaInSn (68.5% Ga, 21.5% In, and 10.0% Sn) alloy as enabled by a sealed closed system with an acidic vapor background; and non-alloying/corrosion-resistant carbon inks for electrical connection. Collectively, this work addresses a wide variety of electromagnetic fundamentals, and the device construction advances required for real-world applications.**

I. Introduction

Having multiple or reconfigurable electromagnetic capabilities within a single device is highly desirable, however, typical devices are limited in reconfigurability [1], [2] compared to actual physical re-arrangement of metal conductors to modify apertures, resonance lengths, etc. There is also increasing interest in physically flexible or conformal electronics, which can improve user ergonomics and facilitate integration into applications where a rigid substrate is not possible. Furthermore, both reconfigurable[3], [4] and physically flexible electromagnetic devices combined, could enable an array of applications that are not being envisioned by those pursuing either attractive attribute alone. Our working group and others have now shown that liquid metals can lead to significant reconfigurable, self-healing, and even stretchable devices. However, previous works have not examined a larger fundamental set of electromagnetic capabilities of fully-sealed and reliable devices that bring experiment closer to application.

We report here, pressure-actuated liquid metal devices (Fig. 1) with fundamental electromagnetic capabilities within the GHz regime spanning tunable dipole antennas, switchable shielding with 35 dB attenuation, ~30 dB polarizer attenuation, and ~40 degree diffraction from a linear grating.

These devices consist of inherently flexible materials, use non-toxic GaInSn (68.5% Ga, 21.5% In, and 10.0% Sn) alloy, employ non-alloying/corrosion-resistant electrodes, and are implemented in a sealed closed-loop system with oxide-preventing acidic vapor background. Although the devices in this work are specifically designed for the GHz regime, simple geometrical scaling can lead to a wider range of applications ranging from MHz to THz. With fundamental capabilities now demonstrated, and requisite device construction better understood, the utility of these liquid metal devices can be more broadly and accurately envisioned for real world applications.

II. Liquid Metal Devices

The devices all rely on a similar construction (Fig. 1), while utilizing competitive liquid metal shaping with Laplace and vacuum pressures. With <10 pounds per square inch (psi) vacuum applied to two flexible films, one film having a network of microreplicated trenches, the Laplace pressure outside the trenches increases, driving the liquid metal into the trenches (lower Laplace pressure). Upon release of vacuum, the channel height returns to its original position, erasing the liquid metal pattern as surface tension dewets the liquid metal into droplets that compacts to 10-100x less area than when in the trenches.

A. Tunable Dipole Antenna

A tunable dipole antenna was assembled using flexible materials such as polydimethylsiloxane (PDMS, Dow Corning Sylgard 184) and porous polyimide (AR Brown-US, 3M101200250). The length of the dipole arms are changed via

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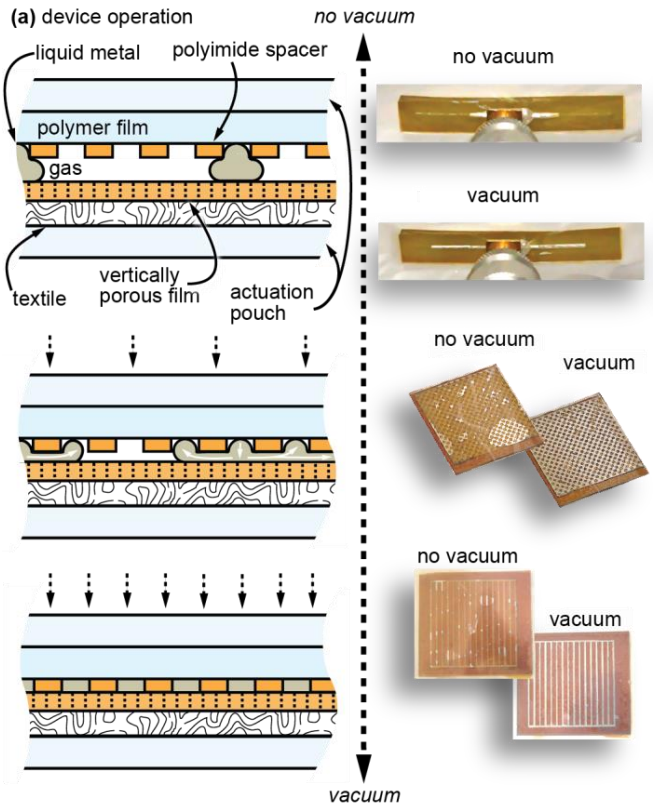

Fig. 1. Diagram of a reversible vacuum pressure-actuated liquid metal device (left) and photographed examples including antennas, shields and polarizers (right, top to bottom).

vacuum pressure (liquid metal dipole length increases with vacuum level, see Fig. 1). The dipole is tunable in terms of this length and therefore the frequency (f) resonance is also tunable according to the following equation.

$$f = \frac{2*c}{L\sqrt{\varepsilon_{eff}}}, \quad (1)$$

where c is the speed of light, L is the length of the dipole and εeff the effective dielectric. As with most antennas a RF electrode connection is to be made. In the applications involving liquid metal one must be concerned with alloying effects. To avoid this, RF electrode connections that are non-alloying with the liquid metal were made by adding a conductive carbon ink protective coating (Henkel, Acheson Electrodag PF-407C).

B. Switchable Shield

A switchable electromagnetic was created using flexible materials such as polyimide and polyethylene terephthalate. The switchable shield reconfigures between multiple compact droplets to a reticulated network formed by circular polyimide spacers that can attenuate incoming microwaves. In a droplet form, in the non-actuated state, the liquid metal only slightly impedes the incoming microwaves as they pass through the device to the power meter, however, in the actuated state the liquid metal spreads through the space formed between

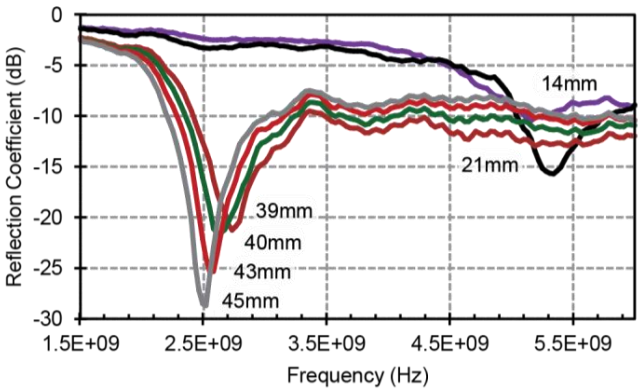

Fig. 2. Measured dipole resonant frequency as the length of the dipole is tuned.

adjacent spacers making a reticulated network and attenuating the microwaves.

C. Switchable Polarizer

A switchable electromagnetic polarizer was created using flexible materials such as polyimide and polyethylene terephthalate. The polarizer reconfigures between multiple compact droplets to metallic lines formed by polyimide spacers. In a droplet form, in the non-actuated state, the liquid metal only slightly impedes the incoming microwaves as they pass through the device to a power meter, however, in the actuated state the liquid metal spreads throughout the space formed between adjacent spacers making a network of metallic lines and attenuating the microwaves based upon the orientation of the lines relative to the incoming microwaves.

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